

# Probing neutrino magnetic moments at Spallation Neutron Source facilities

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## Abstract

Majorana neutrino electromagnetic properties are studied through neutral current coherent neutrino-nucleus scattering. We focus on the potential of the recently planned COHERENT experiment at the Spallation Neutron Source to probe muon-neutrino magnetic moments. The resulting sensitivities are determined on the basis of a  $\chi^2$  analysis employing realistic nuclear structure calculations in the context of the quasiparticle random phase approximation. We find that they can improve existing limits by half an order of magnitude. In addition, we show that these facilities allow for standard model precision tests in the low energy regime, with a competitive determination of the weak mixing angle. Finally, they also offer the capability to probe other electromagnetic neutrino properties, such as the neutrino charge radius. We illustrate our results for various choices of experimental setup and target material.

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## I. INTRODUCTION

The robust confirmation of the existence of neutrino masses and mixing [1, 2], thanks to the milestone discovery of neutrino oscillations in propagation from solar, atmospheric, accelerator, and reactor neutrino sources, has opened a window to probe new physics beyond the standard model (SM) (for the relevant experimental references see e.g. [3, 4]). While the ultimate origin of neutrino mass remains a mystery [5], oscillation results have motivated a plethora of SM extensions to generate small neutrino masses [6]. A generic feature of such models is the existence of nontrivial neutrino electromagnetic (EM) properties [7–12]. Although the three-neutrino oscillation paradigm seems to be on rather solid ground [13, 14], nontrivial neutrino electromagnetic properties may still play an important subleading role in precision neutrino studies [15].

The lowest-order contribution of neutrino EM interactions involves neutrino magnetic moments (NMM) [11, 16, 17], as well as the neutrino charge radius [18–20] arising from loop-level radiative corrections [21, 22]. Note that a direct neutrino magnetic moment measurement could provide a key insight in the understanding of the electroweak interactions, and the Majorana nature of neutrinos [23, 24]. Indeed, in contrast to the case of Majorana neutrinos, only massive Dirac neutrinos can have non-vanishing diagonal magnetic moments [7, 9, 10, 12]. In the general Majorana case, only off-diagonal transition magnetic moments exist, they form an antisymmetric matrix, calculable from first principles, given the underlying gauge theory.

Within the minimally extended  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  model with Dirac neutrino masses, one expects tiny NMM, of the order of  $\mu_\nu \leq 10^{-19} \mu_B \left(\frac{m_\nu}{1\text{eV}}\right)$ , expressed in Bohr magnetons  $\mu_B$  [25, 26]. However, appreciably larger Majorana neutrino transition magnetic moments are expected in many theoretical models, such as those involved with left-right symmetry [27], scalar leptoquarks [28], R-parity-violating supersymmetry [29], and large extra dimensions [30]. Currently, the most stringent upper limits,  $\mu_\nu \leq \text{few} \times 10^{-12} \mu_B$ , come from astrophysics [16, 17, 31, 32]. In addition, there are bounds from measurements by various terrestrial neutrino scattering experiments. The present status of such constraints is summarized in Table I where one can see that the direct constraints on  $\mu_{\nu_\mu}$  and  $\mu_{\nu_e}$  are still rather poor. It should be mentioned, however, that currently operating reactor neutrino experiments such as TEXONO and GEMMA have set robust constraints on  $\mu_{\bar{\nu}_e}$ .

TABLE I: Summary of the current 90% C.L. constraints on neutrino magnetic moments from various experiments.

Experiment	Reaction	Observable	Constraint ( $10^{-10}\mu_B$ )
LSND [33]	$\nu_\mu e^- \rightarrow \nu_\mu e^-$	$\mu_{\nu_\mu}$	6.8
LAMPF [34]	$\nu_e e^- \rightarrow \nu_e e^-$	$\mu_{\nu_e}$	10.8
TEXONO [35]	$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$	$\mu_{\bar{\nu}_e}$	0.74
GEMMA [36]	$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$	$\mu_{\bar{\nu}_e}$	0.29

The possibility of probing neutrino EM parameters, such as the NMM and the neutrino charge radius, through coherent elastic neutrino-nucleus scattering (CENNS) [37, 38] can be explored on the basis of a sensitivity  $\chi^2$ -type analysis [39–45]. To this end here we perform realistic nuclear structure calculations [46, 47] in order to compute accurately the relevant cross sections [48–50]. The required proton and neutron nuclear form factors are reliably obtained within the context of the quasiparticle random phase approximation (QRPA) method by considering realistic strong nuclear forces [51–54]. Concentrating on ongoing and planned neutrino experiments, we have devoted special effort in estimating the expected number of CENNS events with high significance. Specifically, our study is focused on the proposed detector materials of the COHERENT experiment [55, 56] at the Spallation Neutron Source (SNS) [57]. Even though a CENNS event has never been experimentally measured, we remark that the highly intense neutrino beams [58, 59] provided at the SNS indicate very encouraging prospects towards the detection of this reaction for the first time [60, 61], by using low energy detectors [62]. Furthermore, neutrinos from stopped pion-muon beams [63, 64] at the SNS [65, 66] or elsewhere [67, 68] have motivated many studies searching for physics beyond the SM model too [43, 50, 69, 70].

In the present work we quantify the prospects, not only of detecting CENNS events at the SNS, but also of performing precision electroweak measurements and probing neutrino properties beyond the SM. We conclude that the extracted sensitivities on the effective NMM improve with respect to previous results of studies of this type. We obtain for the first time robust upper limits on  $\mu_{\nu_\mu}$ . Moreover, we obtain a sensitivity for the neutrino charge radius, which is competitive with those of previous studies. Furthermore, we explore the sensitivity of these experiments for standard model precision measurements of the weak mixing angle

in the energy regime of few MeV.

## II. COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

The CENNS is described within the SM starting from the neutrino-quark neutral-current (NC) interaction, but is expected to have corrections coming from new physics [3], such as nonstandard interactions [39, 41–45, 49, 50] or nontrivial neutrino electromagnetic properties [70]. Here we focus on the latter [16, 17, 20].

### A. Standard model prediction

At low and intermediate neutrino energies  $E_\nu \ll M_W$ , the weak neutral-current cross section describing this process in the SM is given by the four-fermion effective interaction Lagrangian,  $\mathcal{L}_{\text{SM}}$ ,

$$\mathcal{L}_{\text{SM}} = -2\sqrt{2}G_F \sum_{\substack{f=u,d \\ \alpha=e,\mu,\tau \\ P=L,R}} g_{\alpha\alpha}^{f,P} [\bar{\nu}_\alpha \gamma_\rho L \nu_\alpha] [\bar{f} \gamma^\rho P f] , \quad (1)$$

where  $P = \{L, R\}$  are the chiral projectors,  $\alpha = \{e, \mu, \tau\}$  denotes the neutrino flavor,  $f$  is a first generation quark, and  $G_F$  is the Fermi constant. The left- and right-hand coupling constants for the  $u$ - and  $d$ -quark to the  $Z$ -boson including the relevant radiative corrections are given as [15]

$$\begin{aligned} g_{\alpha\alpha}^{u,L} &= \rho_{\nu N}^{NC} \left( \frac{1}{2} - \frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{u,L} , \\ g_{\alpha\alpha}^{d,L} &= \rho_{\nu N}^{NC} \left( -\frac{1}{2} + \frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{d,L} , \\ g_{\alpha\alpha}^{u,R} &= \rho_{\nu N}^{NC} \left( -\frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{u,R} , \\ g_{\alpha\alpha}^{d,R} &= \rho_{\nu N}^{NC} \left( \frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{d,R} , \end{aligned} \quad (2)$$

with  $\hat{s}_Z^2 = \sin^2 \theta_W = 0.23120$ ,  $\rho_{\nu N}^{NC} = 1.0086$ ,  $\hat{\kappa}_{\nu N} = 0.9978$ ,  $\lambda^{u,L} = -0.0031$ ,  $\lambda^{d,L} = -0.0025$  and  $\lambda^{d,R} = 2\lambda^{u,R} = 7.5 \times 10^{-5}$ .

Since neutrino detection experiments are sensitive to the kinetic energy of the recoiling nucleus, one expresses the differential cross section accordingly. Using the effective Lagrangian of Eq. (1), one can describe the coherent neutrino scattering off a spherical spin-zero nucleus

of mass  $M$ , by computing the differential cross section with respect to the nuclear recoil energy,  $T$ , as [49, 50]

$$\left(\frac{d\sigma}{dT}\right)_{\text{SM}} = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \left|\langle gs || \hat{\mathcal{M}}_0(q) || gs \rangle\right|^2, \quad (3)$$

where  $E_\nu$  is the neutrino energy. Within the context of the Donnelly-Walecka multipole decomposition method, the relevant nuclear matrix element for the dominant coherent channel ( $gs \rightarrow gs$  transitions) is based on the Coulomb operator  $\hat{\mathcal{M}}_0$  [51]. The latter is a product of the zero-order spherical Bessel function times the zero-order spherical harmonic [48, 52–54] and can be cast in the form [49]

$$|\mathcal{M}_V^{\text{SM}}|^2 \equiv \left|\langle gs || \hat{\mathcal{M}}_0(q) || gs \rangle\right|^2 = [g_V^p Z F_Z(q^2) + g_V^n N F_N(q^2)]^2. \quad (4)$$

The finite nuclear size is taken into account by expressing the Coulomb matrix element in terms of the proton (neutron) nuclear form factors  $F_{Z(N)}(q^2)$ , reflecting the dependence of the coherent rate on the variation of the momentum transfer,  $q^2 \simeq 2MT$ . The polar-vector couplings of protons ( $g_V^p$ ) and neutrons ( $g_V^n$ ) to the  $Z$ -boson are defined as  $g_V^p = 2(g_{\alpha\alpha}^{u,L} + g_{\alpha\alpha}^{u,R}) + (g_{\alpha\alpha}^{d,L} + g_{\alpha\alpha}^{d,R})$  and  $g_V^n = (g_{\alpha\alpha}^{u,L} + g_{\alpha\alpha}^{u,R}) + 2(g_{\alpha\alpha}^{d,L} + g_{\alpha\alpha}^{d,R})$ , respectively. It can be noticed that the vector proton coupling,  $g_V^p$ , is small compared to the corresponding neutron coupling,  $g_V^n$ , therefore, the dominant contribution to the coherent cross section scales with the square of the number of neutrons of the target isotope.

In this work we perform realistic nuclear structure calculations for the experimentally interesting even-even nuclear isotopes,  $^{20}\text{Ne}$ ,  $^{40}\text{Ar}$ ,  $^{76}\text{Ge}$  and  $^{132}\text{Xe}$ . To this aim, the nuclear ground state,  $|gs\rangle \equiv |0^+\rangle$ , has been constructed by solving (iteratively) the BCS equations, quite precisely. In this framework, the proton (neutron) nuclear form factors read [46]

$$F_{N_n}(q^2) = \frac{1}{N_n} \sum_j \sqrt{2j+1} \langle j | j_0(qr) | j \rangle (v_{N_n}^j)^2, \quad (5)$$

where  $N_n = Z$  (or  $N$ ) and  $v_{N_n}^j$  denotes the occupation probability amplitude of the  $j$ th single-nucleon level. For each nuclear system, the chosen active model space, as well as the required monopole (pairing) residual interaction that was obtained from a Bonn C-D two-body potential (strong two-nucleon forces) and slightly renormalized with two parameters  $g_{\text{pair}}^{p(n)}$  for proton (neutron) pairs, has been taken from Ref. [50]. The above method has been successfully applied for similar calculations of various semileptonic nuclear processes [47, 52, 54].

## B. Electromagnetic neutrino-nucleus cross sections

After the discovery of neutrino oscillations [13, 14] over a decade ago, it became evident that neutrinos are indeed massive particles [1, 2] and, as a result, they may acquire nontrivial electromagnetic properties as well [23, 24]. At low-momentum transfer, the description of possible neutrino EM interactions involves two types of phenomenological parameters, the anomalous magnetic moment and the mean-square charge radius [7–12]. It is worth mentioning that the photon exchange involving a neutrino magnetic moment flips the neutrino helicity, while in the interaction due to the weak gauge boson exchange the helicity is preserved.

The electromagnetic neutrino-nucleus vertex has been comprehensively studied [26], and its contribution to the coherent elastic cross section including nuclear physics details takes the form [70]

$$\left(\frac{d\sigma}{dT}\right)_{\text{EM}} = \frac{\pi\alpha_{\text{em}}^2\mu_{\text{eff}}^2 Z^2}{m_e^2} \left(\frac{1 - T/E_\nu}{T}\right) F_Z^2(q^2), \quad (6)$$

where  $\alpha_{\text{em}}$  is the fine structure constant and  $\mu_{\text{eff}}$  is the effective neutrino magnetic moment.

In this framework, the helicity preserving standard weak interaction cross section (SM) adds incoherently with the helicity-violating EM cross section, so the total cross section is written as

$$\left(\frac{d\sigma}{dT}\right)_{\text{tot}} = \left(\frac{d\sigma}{dT}\right)_{\text{SM}} + \left(\frac{d\sigma}{dT}\right)_{\text{EM}}. \quad (7)$$

The latter expression will be used below in order to constrain the effective neutrino magnetic moment parameters.

## III. NEUTRINOS FROM THE SPALLATION NEUTRON SOURCE

There are several experimental proposals that plan to detect for the first time a CENNS [65–68] signal. In this section, we describe the ongoing COHERENT experiment [55, 56], proposed to operate at the SNS at Oak Ridge National Lab [57]. This facility provides excellent prospects for measuring CENNS events for the first time. In general, any potential deviation from the SM expectations can be directly interpreted as a signature of new physics and, thus, has prompted many theoretical studies searching for physics within [60, 61] and beyond the SM [40, 41, 43, 50, 69].

Currently, the SNS constitutes the leading facility for neutron physics searches, producing neutrons by firing a pulsed proton beam at a liquid mercury target [65]. In addition to neutrons, the mercury target generates pions, which decay producing neutrino beams as a free by-product. These beams are exceptionally intense, of the order of  $\Phi = 2.5 \times 10^7 \nu \text{ s}^{-1} \text{ cm}^{-2}$  ( $\Phi = 6.3 \times 10^6 \nu \text{ s}^{-1} \text{ cm}^{-2}$ ) per flavor at 20 m (40 m) from the spallation target [58]. In stopped pion-muon sources, a monoenergetic muon-neutrino  $\nu_\mu$  flux with energy 29.9 MeV is produced via pion decay at rest  $\pi^+ \rightarrow \mu^+ \nu_\mu$  within  $\tau = 26 \text{ ns}$  (prompt flux), followed by electron neutrinos,  $\nu_e$ , and muon antineutrinos,  $\bar{\nu}_\mu$ , that are emitted from the muon-decay  $\mu^+ \rightarrow \nu_e e^+ \bar{\nu}_\mu$  within  $\tau = 2.2 \mu\text{s}$  (delayed flux) [59]. The  $\nu_e$  and  $\bar{\nu}_\mu$  neutrino spectra are described at rather high precision by the normalized distributions [63, 64]

$$\begin{aligned}\eta_{\nu_e}^{SNS} &= 96 E_\nu^2 M_\mu^{-4} (M_\mu - 2E_\nu) , \\ \eta_{\bar{\nu}_\mu}^{SNS} &= 16 E_\nu^2 M_\mu^{-4} (3M_\mu - 4E_\nu) ,\end{aligned}\tag{8}$$

with maximum energy of  $E_\nu^{\text{max}} = M_\mu/2$ , ( $M_\mu = 105.6 \text{ MeV}$  is the muon rest mass).

In this work we distinguish two cases, the optimistic and the realistic ones. The first case is convenient for exploring the nuclear responses of different nuclear detector isotopes, in order to get a first idea of the relevant neutrino parameters within and beyond the SM. The second

TABLE II: Summary of the detector concepts assumed in this work. We consider four possible nuclei as targets and two possible experimental setups for each nucleus, a realistic one, for different detector masses, distances, recoil energy windows, and efficiencies, and the optimistic case where all the variables are allowed to have their “best” value.

COHERENT experiment					
		$^{20}\text{Ne}$ [55]	$^{40}\text{Ar}$ [55]	$^{76}\text{Ge}$ [69]	$^{132}\text{Xe}$ [55, 62]
Realistic	Mass	391 kg	456 kg	100 kg	100 kg
	Distance	46 m	46 m	20 m	40 m
	Efficiency	50%	50%	67%	50%
	Recoil window	30-160 keV	20-120 keV	10-78 keV	8-46 keV
Optimistic	mass	1 ton	1 ton	1 ton	1 ton
	Distance	20 m	20 m	20 m	20 m
	Efficiency	100%	100%	100%	100%
	Recoil window	$1\text{keV} - T_{\text{max}}$	$1\text{keV} - T_{\text{max}}$	$1\text{keV} - T_{\text{max}}$	$1\text{keV} - T_{\text{max}}$

case is useful in quantifying the sensitivities attainable with various individual technologies of each experimental setup. Both cases are useful and complementary to illustrate the potential of the proposal. For instance, for the realistic case, the original COHERENT proposal considers different detectors to be located in different rooms and, therefore, at different distances. In particular, the  $^{132}\text{Xe}$  detector is considered to be 40 m from the source while other isotopes are expected to be 20 m. Clearly, for shorter distances the attainable sensitivities would be higher for any of these detectors; this possibility is considered in the optimistic case.

In our calculations, we assume a time window of one year for the optimistic case and  $2.4 \times 10^7$  s for the realistic case [66]. Detailed information on the different detector setups considered here is summarized in Table II. For a comprehensive description of the relevant nuclear isotopes including the experimental criteria and advantages of adopting each of them, the reader is referred to Refs. [40, 50].

#### IV. NUMERICAL RESULTS

Assuming negligible neutrino oscillation effects in short-distance propagation, for each interaction channel,  $x = \text{SM, EM, tot}$ , the total number of counts above a certain threshold,  $T_{thres}$ , is given through the expression

$$N_x^{events} = K \int_{E_{\nu min}}^{E_{\nu max}} \eta^{SNS}(E_{\nu}) dE_{\nu} \int_{T_{thres}}^{T_{max}} \left( \frac{d\sigma}{dT}(E_{\nu}, T) \right)_x dT, \quad (9)$$

where  $K = N_{targ} t_{tot} \Phi$ , with  $N_{targ}$  being the total number of atomic targets in the detector,  $t_{tot}$  the time window of data taking, and  $\Phi$  the total neutrino flux. In the present calculations, the various experimental concepts are taken into account by fixing the corresponding input parameters as discussed previously.

##### A. Standard model precision tests at SNS

We first examine the sensitivity of the COHERENT experiment to the weak mixing angle  $\sin^2 \theta_W$  of the SM in the low energy regime of the SNS operation. In order to quantify this sensitivity, assuming that the experimental proposal will measure exactly the SM prediction,



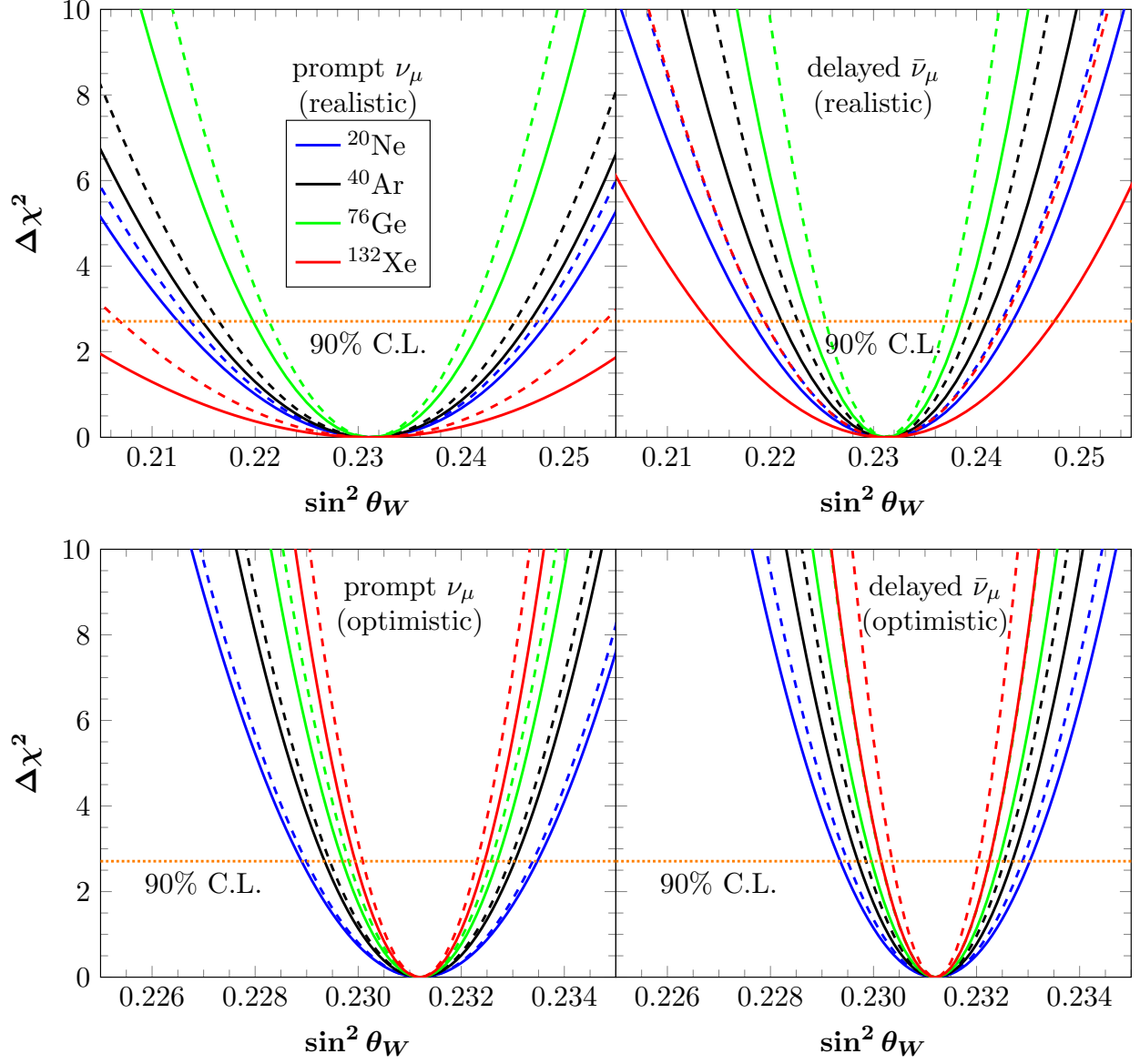


FIG. 1:  $\Delta\chi^2$  profile in terms of the weak mixing angle  $\sin^2\theta_W$  showing the sensitivity of the COHERENT experiment to SM precision tests. The Particle Data Group value  $\hat{s}_Z^2 = 0.23120$ , is used as the central value. Left (right) panels illustrate the results obtained by considering the prompt (delayed) flux, while upper (lower) panels account for the realistic (optimistic) case. Here, the solid (dashed) lines refer to the nuclear BCS method (zero-momentum transfer).

we perform a statistical analysis based on a  $\chi^2$  with statistical errors only

$$\chi^2 = \left( \frac{N_{SM}^{events} - N_{SNS}^{events}(\sin^2\theta_W)}{\delta N_{SM}^{events}} \right)^2, \quad (10)$$

where the number of SM events,  $N_{SM}^{events}$ , depends on the Coulomb nuclear matrix element entering the coherent rate. As the central value for the SM weak mixing angle prediction we adopt the PDG value  $\hat{s}_Z^2 = 0.23120$ . We then compute the  $\chi^2$  function depending on the expected number of events for a given value of the mixing angle,  $N_{SNS}^{events}(\sin^2 \theta_W)$ . The corresponding results for the various detector materials of the COHERENT experiment are shown in Fig. 1. In Table III, we illustrate the band,  $\delta \sin^2 \theta_W \equiv \delta s_W^2$ , at 90% C.L. evaluated as  $\delta s_W^2 = (s_{Wmax}^2 - s_{Wmin}^2)/2$  and the corresponding uncertainty  $\delta s_W^2 / \hat{s}_Z^2$ , with  $s_{Wmax}^2$  and  $s_{Wmin}^2$  being the upper and lower  $1\sigma$  error, respectively. At the optimistic level, our results indicate that better sensitivities are expected for heavier target nuclei, such as  $^{132}\text{Xe}$ . This is understood as a direct consequence of the significantly larger number of expected events provided by heavier nuclear isotopes [50]. However, once we consider the realistic case, the expectations change drastically so that, for the case of a  $^{76}\text{Ge}$  detector we find a better sensitivity, due to a closer location to the SNS source (20 m in comparison with the 40 m

TABLE III: Expected sensitivities to the weak mixing angle  $\sin^2 \theta_W(\nu_\alpha) \equiv s_W^2(\nu_\alpha)$ , assuming the various channels  $(\nu_\mu, \bar{\nu}_\mu, \nu_e)$  of the SNS beam for a set of possible detectors at the COHERENT experiment. For the realistic [optimistic] case, the band  $\delta s_W^2(\nu_\alpha)$  and the corresponding uncertainty are evaluated within  $1\sigma$  error.

Nucleus	$\delta s_W^2(\nu_\mu)$	Uncer. (%)	$\delta s_W^2(\bar{\nu}_\mu)$	Uncer. (%)	$\delta s_W^2(\nu_e)$	Uncer. (%)
$^{20}\text{Ne}$	0.0110	4.74	0.0077	3.33	0.0091	3.94
	[0.0014]	[0.61]	[0.0011]	[0.48]	[0.0013]	[0.56]
$^{40}\text{Ar}$	0.0097	4.17	0.0061	2.64	0.0074	3.20
	[0.0011]	[0.48]	[0.0009]	[0.39]	[0.0010]	[0.43]
$^{76}\text{Ge}$	0.0068	2.94	0.0045	1.92	0.0055	2.36
	[0.0009]	[0.39]	[0.0008]	[0.35]	[0.0009]	[0.37]
$^{132}\text{Xe}$	0.0181	7.83	0.0102	4.39	0.0127	5.47
	[0.0008]	[0.35]	[0.0006]	[0.26]	[0.0007]	[0.30]

TABLE IV: Expected sensitivities to the weak mixing angle  $\sin^2 \theta_W(\nu_\mu) \equiv s_W^2(\nu_\mu)$ , through a combined analysis of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ). Same conventions as in Table III are used.

Nucleus	$^{20}\text{Ne}$	$^{40}\text{Ar}$	$^{76}\text{Ge}$	$^{132}\text{Xe}$
$\delta s_W^2(\nu_\mu)$	0.0052 [0.0007]	0.0042 [0.0006]	0.0031 [0.0005]	0.0073 [0.0004]
Uncer. (%)	2.23 [0.30]	1.82 [0.26]	1.34 [0.22]	3.14 [0.17]

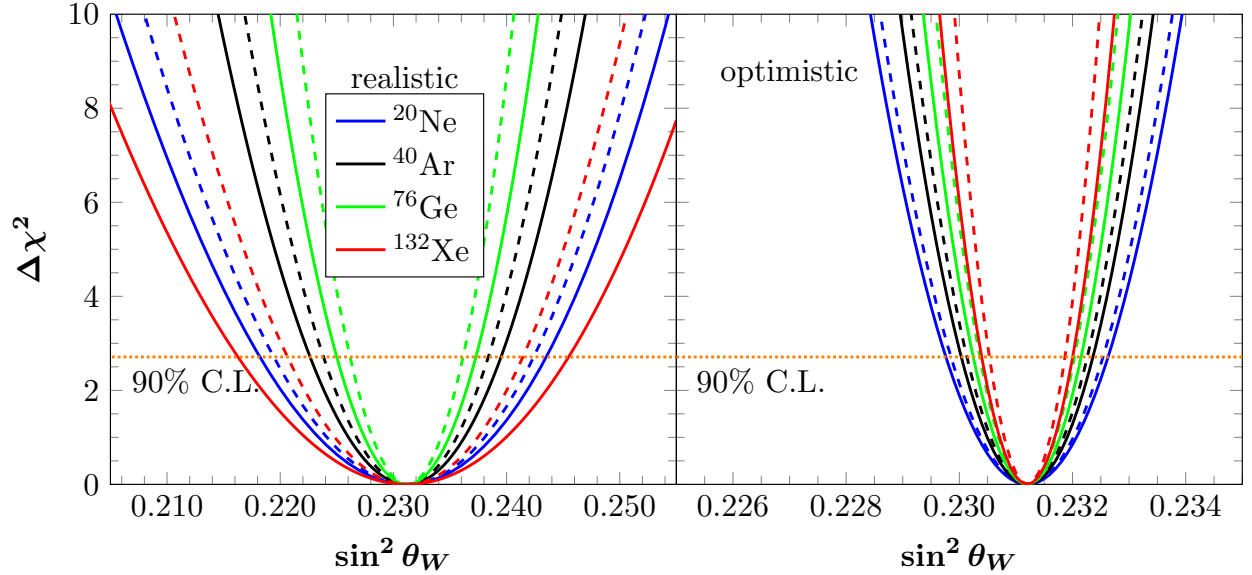


FIG. 2:  $\Delta\chi^2$  profile in terms of the weak mixing angle  $\sin^2 \theta_W$  from the combined measurement of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ). Same conventions as in Fig. 1 are used.

for the  $^{132}\text{Xe}$  case) and a higher efficiency in recoil acceptance (see Table II). Furthermore, in Fig. 2 and Table IV, we show that the expected sensitivities improve through a combined measurement of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ).

## B. EM neutrino interactions at SNS

One of the main goals of our present work is to examine the sensitivity of the COHERENT experiment to the possible detection of CENNS events due to neutrino EM effects, associated

TABLE V: Upper limits on the neutrino magnetic moment (in units of  $10^{-10}\mu_B$ ) at 90% C.L. expected at the COHERENT experiment for the realistic (optimistic) case. The results indicated with  $(^{\text{comb}})$  are obtained from a combined measurement of the prompt and delayed beams.

Nucleus	$^{20}\text{Ne}$	$^{40}\text{Ar}$	$^{76}\text{Ge}$	$^{132}\text{Xe}$
$\mu_{\nu_\mu}$	9.09 [2.31]	9.30 [2.47]	8.37 [2.54]	12.94 [2.54]
$\mu_{\bar{\nu}_\mu}$	10.28 [2.53]	10.46 [2.69]	9.39 [2.75]	14.96 [2.74]
$\mu_{\nu_e}$	10.22 [2.44]	10.55 [2.60]	9.46 [2.68]	15.20 [2.68]
$\mu_{\nu_\mu}^{\text{comb}}$	8.07 [2.02]	8.24 [2.16]	7.41 [2.22]	11.58 [2.21]

with various effective transition NMM parameters such as  $\mu_{\nu_\mu}$ ,  $\mu_{\bar{\nu}_\mu}$ , and  $\mu_{\nu_e}$ . The total number of events expected in an experiment searching for CENNS depends strongly on the energy threshold  $T_{\text{thres}}$  as well as the total mass of the detector. For low energy thresholds and more massive detectors, the total number of events expected is significantly larger and, therefore, the attainable constraints are more stringent. We remind the reader that, for a possible NMM detection, a very low energy threshold is required, since the EM cross section dominates at low energies.

The sensitivity is evaluated by assuming that a given experiment searching for CENNS events, will measure exactly the SM expectation; thus any deviation is understood as a signature of new physics. Following [24] we define the  $\chi^2$  function as

$$\chi^2 = \left( \frac{N_{SM}^{\text{events}} - N_{\text{tot}}^{\text{events}}(\mu_{\nu_\alpha})}{\delta N_{SM}^{\text{events}}} \right)^2. \quad (11)$$

By employing the aforementioned method, we find that the COHERENT experiment could provide useful complementary limits on  $\mu_{\nu_\mu}$ . On the other hand, the sensitivity to  $\mu_{\nu_e}$ , is not expected to be as good as that of reactor experiments [35, 36]. However, a combined analysis of the prompt and delayed muon-neutrino beams ( $\nu_\mu + \bar{\nu}_\mu$ ), could help to further improve the sensitivity to a neutrino magnetic moment. The same applies to the combination of different detectors using the same neutrino source. For different nuclear targets, the present results are shown in Figs. 3 and 4 and the sensitivities on neutrino magnetic moments at 90% C.L. are summarised in Table V.

The sensitivity to neutrino magnetic moments has also been computed for the case of a combined measurement with different target nuclei. In this framework, we take advantage

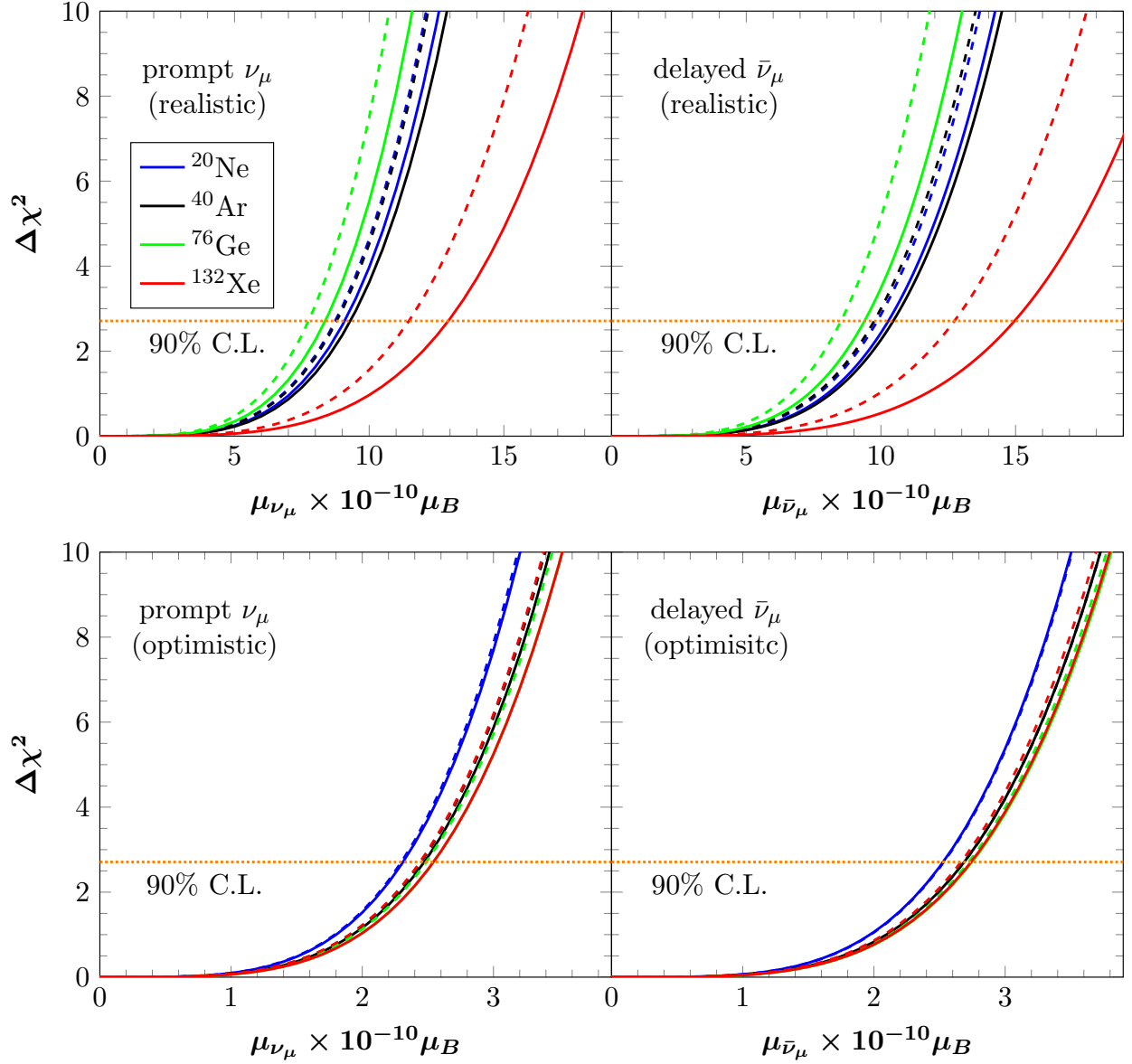


FIG. 3:  $\Delta\chi^2$  profiles for a neutrino magnetic moment,  $\mu_{\nu\mu}$  in units of  $10^{-10}\mu_B$ , of the COHERENT experiment, assuming various nuclear detectors. The same conventions as in Fig. 1 are used.

of the multitarget strategy of the COHERENT experiment [55, 56] and define the  $\chi^2$  as

$$\chi^2 = \sum_{nuclei} \left( \frac{N_{SM}^{events} - N_{tot}^{events}(\mu_{\nu\alpha})}{\delta N_{SM}^{events}} \right)^2. \quad (12)$$

Assuming two nuclear targets at a time and taking into consideration the experimental technologies discussed previously, we have found that among all possible combinations the most stringent sensitivity corresponds to a combined measurement of  $^{20}\text{Ne}+^{76}\text{Ge}$ , which for

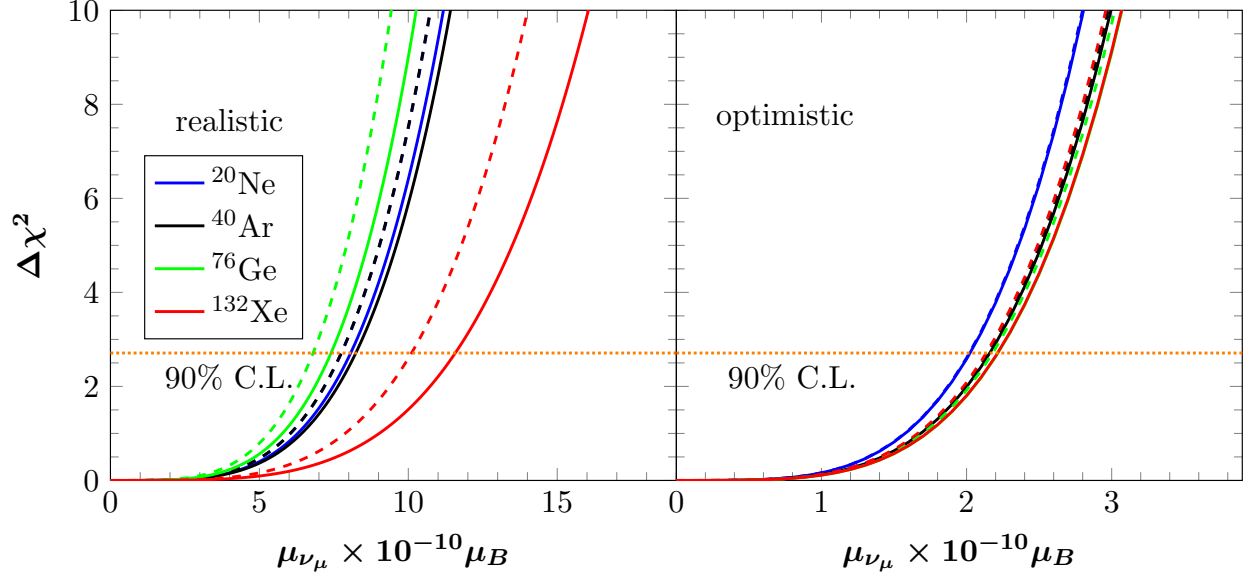


FIG. 4:  $\Delta\chi^2$  profile for a neutrino magnetic moment,  $\mu_{\nu_\mu}$ , in units of  $10^{-10}\mu_B$ , from the combined measurement of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ). The same conventions as in Fig. 1 are used.

the realistic (optimistic) case reads

$$\mu_{\nu_\mu} = 6.48 (1.77) \times 10^{-10} \mu_B \quad 90\% \text{ C.L.} \quad (13)$$

The above sensitivity is better than the case with only one detector. Notice also that the optimistic sensitivity shown here gives an idea to the potential constraint that could be achieved by improving the experimental setup. Moreover, a combined measurement of all possible target nuclei would lead to somewhat better expected sensitivities, i.e.,

$$\mu_{\nu_\mu} = 5.87 (1.52) \times 10^{-10} \mu_B \quad 90\% \text{ C.L.} \quad (14)$$

Eventually, we explore the possibility of varying more than one parameter at the same time. To this aim, a  $\chi^2$  analysis is performed, but in this case the fitted parameters were simultaneously varied. Within this context, the contours of the  $\sin^2 \theta_W - \mu_\nu$  parameter space at 90% C.L. are illustrated in Fig. 5. Finally, in Fig. 6 the allowed regions of the parameter space in the  $\mu_{\bar{\nu}_\mu} - \mu_{\nu_e}$  plane are shown, where the corresponding results have been evaluated at 90% C.L.

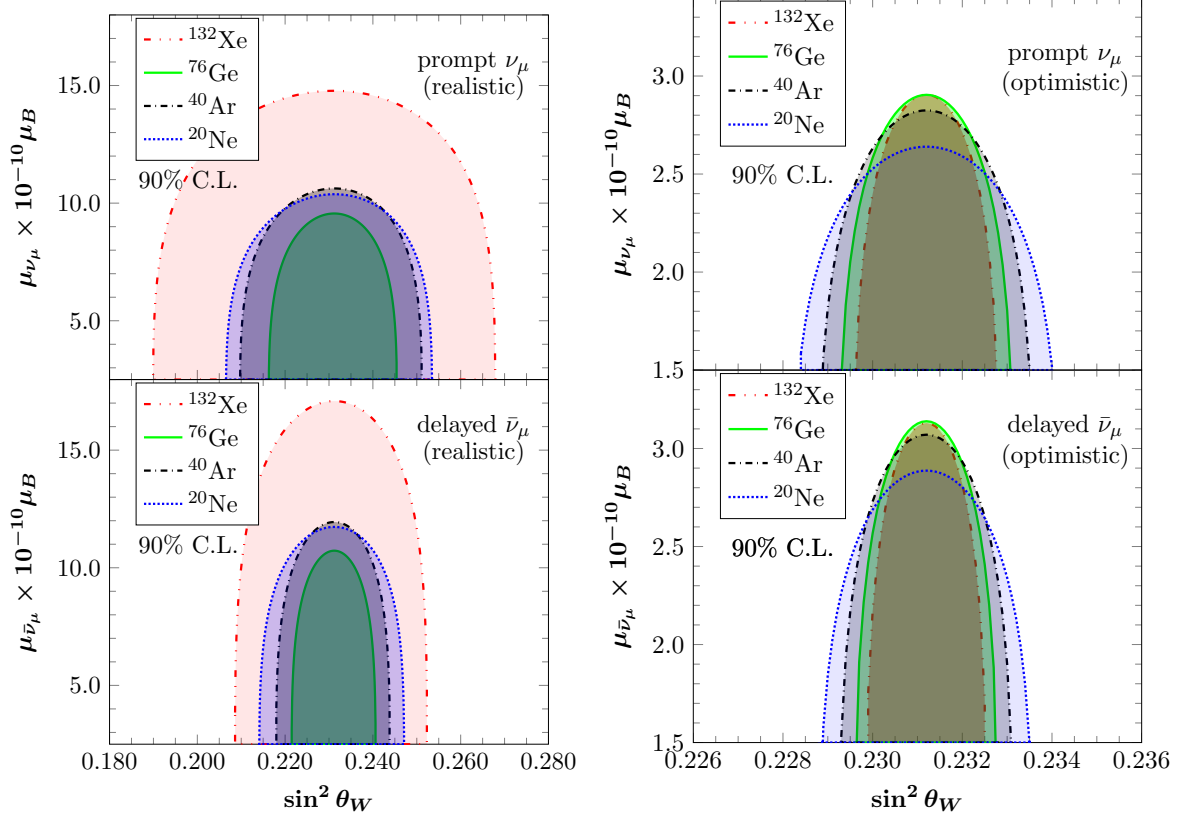


FIG. 5: The  $\mu_{\nu_\mu}(\mu_{\bar{\nu}_\mu})$ - $\sin^2 \theta_W$  contours obtained from a two parameter  $\chi^2$  analysis. Allowed regions are shown for 90% C.L. Left (right) panels account for the realistic (optimistic) case, while the upper (lower) panels refer to the prompt (delayed) flux.

## V. DISCUSSION AND CONCLUSIONS

We have studied the sensitivities on Majorana neutrino magnetic moments attainable through neutral current coherent neutrino-nucleus scattering cross section calculations at the Spallation Neutron Source. Regarding the meaning of the parameter  $\mu_{eff}$  describing the effective neutrino magnetic moment, in general this can be expressed through neutrino amplitudes of positive and negative helicity states (which we denote as the 3-vectors  $a_+$  and  $a_-$ , respectively) and the magnetic moment matrix,  $\lambda$ . Within this notation, the effective neutrino magnetic moment reads [23]

$$\mu_{eff}^2 = a_+^\dagger \lambda \lambda^\dagger a_+ + a_-^\dagger \lambda \lambda^\dagger a_- . \quad (15)$$

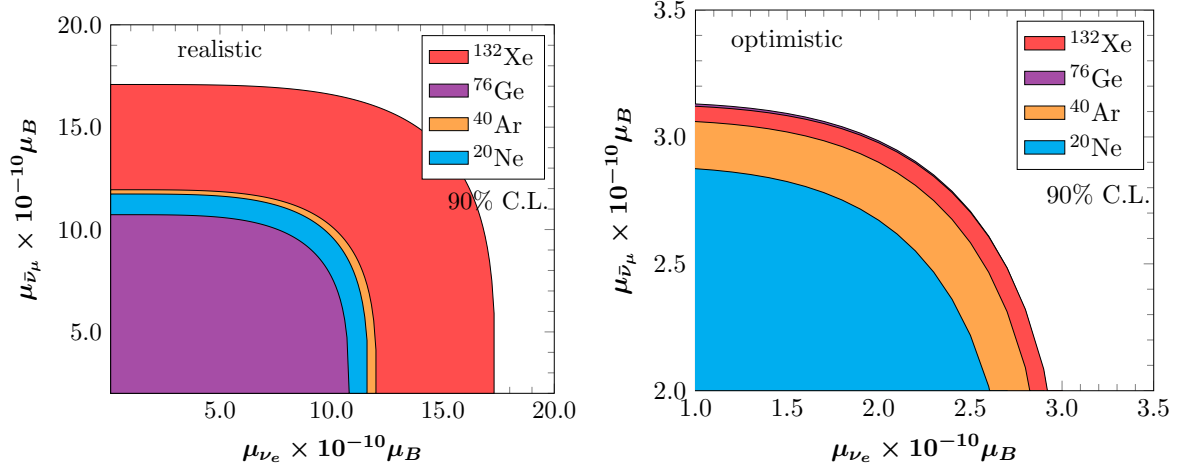


FIG. 6: The  $\mu_{\bar{\nu}_\mu}$ - $\mu_{\nu_e}$  contours obtained from a two parameter  $\chi^2$  analysis. Allowed regions are shown for 90% C.L. Left (right) panel accounts for the realistic (optimistic) case.

In this work, we mainly focus on the muon-neutrino signal. Then, considering the muon-neutrino as having a Majorana nature, we have, in the flavor basis

$$\mu_{eff}^2 = |\Lambda_e|^2 + |\Lambda_\tau|^2, \quad (16)$$

with  $|\Lambda_e|$  and  $|\Lambda_\tau|$  being the elements of the neutrino transition magnetic moment matrix  $\lambda$  describing the corresponding transitions from the muon-neutrino to the tau and electron antineutrino states, respectively. The latter expression can be translated into the mass basis through a rotation by using the leptonic mixing matrix. An analogous expression can be found for purely electron neutrino states, for example. One can see that the limits on the effective neutrino magnetic moment obtained from neutrino experiments are in reality a restriction on a combination of physical observables. In this sense, an improvement in the muon effective neutrino magnetic moment will contribute towards improving the constraints on the physical observables through a combined analysis of neutrino data. A full description of this formalism can be found in Ref. [23].

The sensitivities we have extracted are obtained by means of a simple  $\chi^2$  analysis employing realistic nuclear structure calculations within the QRPA, for the evaluation of the coherent cross section. We find that current limits on the muon-neutrino magnetic moment,  $\mu_{\nu_\mu}$ , can be improved by half an order of magnitude. In addition, we show that the SNS allows for a competitive determination of the electroweak mixing angle  $\theta_W$ . Moreover, the COHERENT proposal may provide an excellent probe for investigating other electromag-



netic neutrino properties, such as the neutrino charge radius (see the appendix). In view of the operation of proposed sensitive neutrino experiments (e.g. COHERENT) our results, presented for various choices of experimental setups and target materials, may contribute towards a deeper understanding of so-far hidden neutrino properties.

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### APPENDIX Sensitivity to the Neutrino Charge Radius

Apart from the neutrino magnetic moment, the neutrino charge radius is another interesting electromagnetic property to be considered. In general, the electric form factor allows us to extract nontrivial information concerning the neutrino electric properties, despite its neutral electric charge [12]. In fact, the gauge-invariant definition of the neutrino effective charge radius  $\langle r_{\nu_\alpha}^2 \rangle$ ,  $\alpha = e, \mu, \tau$ , was proposed long ago [21, 22] as a physical observable related to the vector and axial vector form factors involving the EM interaction of a Dirac neutrino [8, 26]. In particular, at the one-loop approximation a correction of a few percent to the weak mixing angle has been obtained [18–20],

$$\sin^2 \theta_W \rightarrow \sin^2 \overline{\theta}_W + \frac{\sqrt{2}\pi\alpha_{\text{em}}}{3G_F} \langle r_{\nu_\alpha}^2 \rangle. \quad (17)$$

Through CENNS, we estimate for the first time the sensitivity of a low energy SNS experiment to constrain the neutrino charge radius. The obtained bounds are derived in the context of a  $\chi^2$  analysis in the same spirit of the discussion made above and they are presented in Figs. 7 and 8 and listed in Table VI. As expected, the results behave similarly to the case

of the weak mixing angle; thus we conclude that for the realistic (optimistic) case a 100 kg  $^{76}\text{Ge}$  (heavy  $^{132}\text{Xe}$ ) detector at 20 m is required to constrain more significantly the neutrino charge radius. Furthermore, through a combined measurement of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ) an appreciably improved sensitivity can be reached for  $\langle r_{\nu_\mu}^2 \rangle$  in comparison to  $\langle r_{\nu_e}^2 \rangle$ . These sensitivities are better than current ones (see Ref. [12] and references therein) and depending on the detector setup may improve by one order of magnitude.

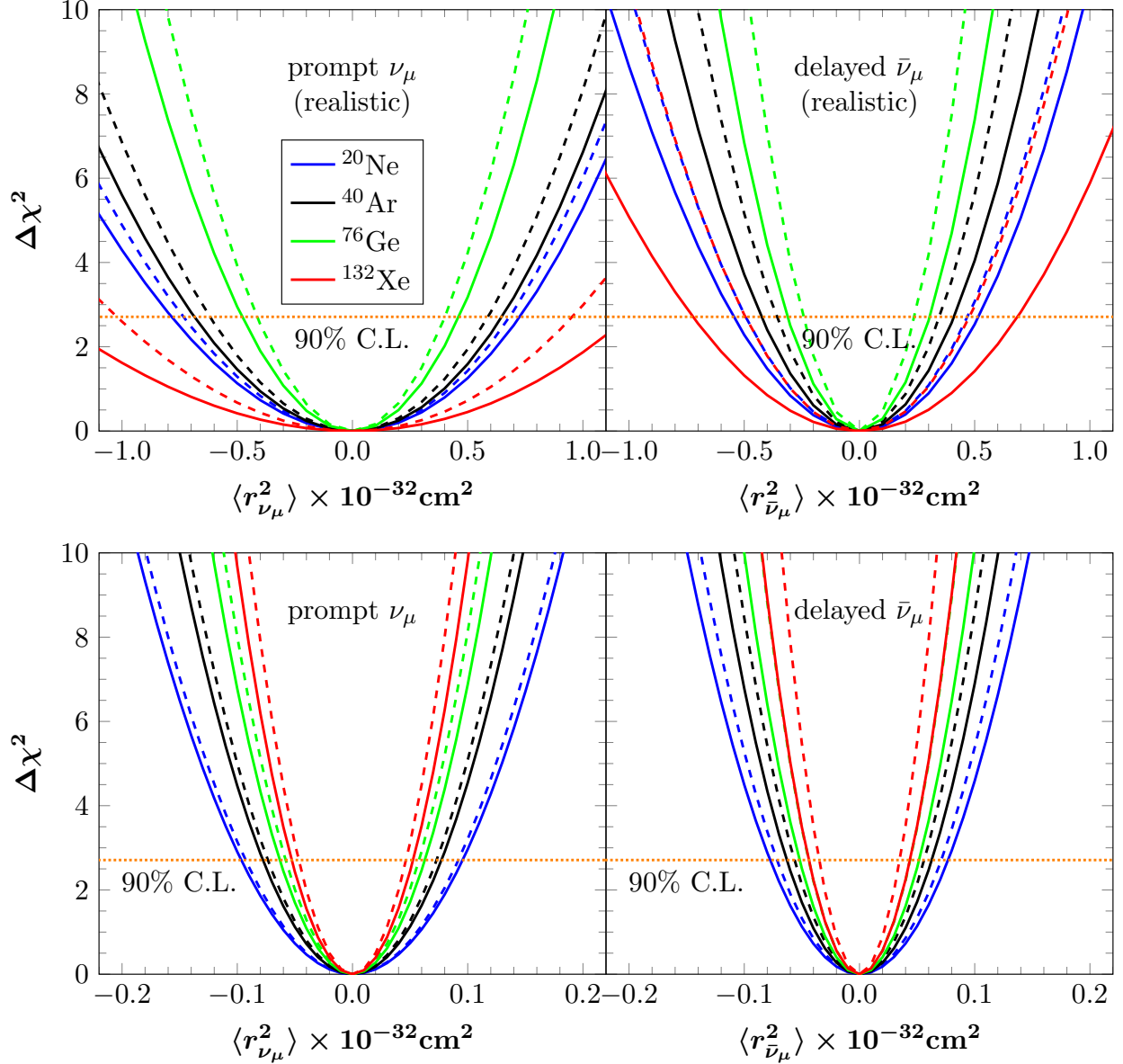


FIG. 7:  $\Delta\chi^2$  profiles for a neutrino charge radius,  $\langle r_{\nu_\mu}^2 \rangle$  in units of  $10^{-32}\text{cm}^2$ , of the COHERENT experiment, assuming various nuclear detectors. Same conventions as in Fig. 1 are used.

TABLE VI: Expected sensitivities on the neutrino charge radius (in units of  $10^{-32}\text{cm}^2$ ) from the analysis of the COHERENT experiment. The limits are presented at 90% C.L. for the realistic (optimistic) case. The results indicated with  $(^{\text{comb}})$  are obtained from a combined measurement of the prompt and delayed beams.

Nucleus	$^{20}\text{Ne}$	$^{40}\text{Ar}$	$^{76}\text{Ge}$	$^{132}\text{Xe}$
$\langle r_{\bar{\nu}_\mu}^2 \rangle$	-0.55 – 0.52 [-0.08 – 0.08]	-0.43 – 0.41 [-0.06 – 0.06]	-0.31 – 0.30 [-0.05 – 0.05]	-0.72 – 0.69 [-0.04 – 0.04]
$\langle r_{\nu_\mu}^2 \rangle$	-0.79 – 0.73 [-0.10 – 0.10]	-0.69 – 0.65 [-0.08 – 0.08]	-0.48 – 0.46 [-0.06 – 0.06]	-1.31 – 1.20 [-0.05 – 0.05]
$\langle r_{\nu_e}^2 \rangle$	-0.65 – 0.61 [-0.09 – 0.09]	-0.53 – 0.50 [-0.07 – 0.07]	-0.38 – 0.37 [-0.06 – 0.06]	-0.90 – 0.85 [-0.05 – 0.05]
$\langle r_{\nu_\mu}^2 \rangle^{\text{comb}}$	-0.44 – 0.42 [-0.06 – 0.06]	-0.36 – 0.35 [-0.05 – 0.05]	-0.26 – 0.26 [-0.04 – 0.04]	-0.63 – 0.60 [-0.03 – 0.03]

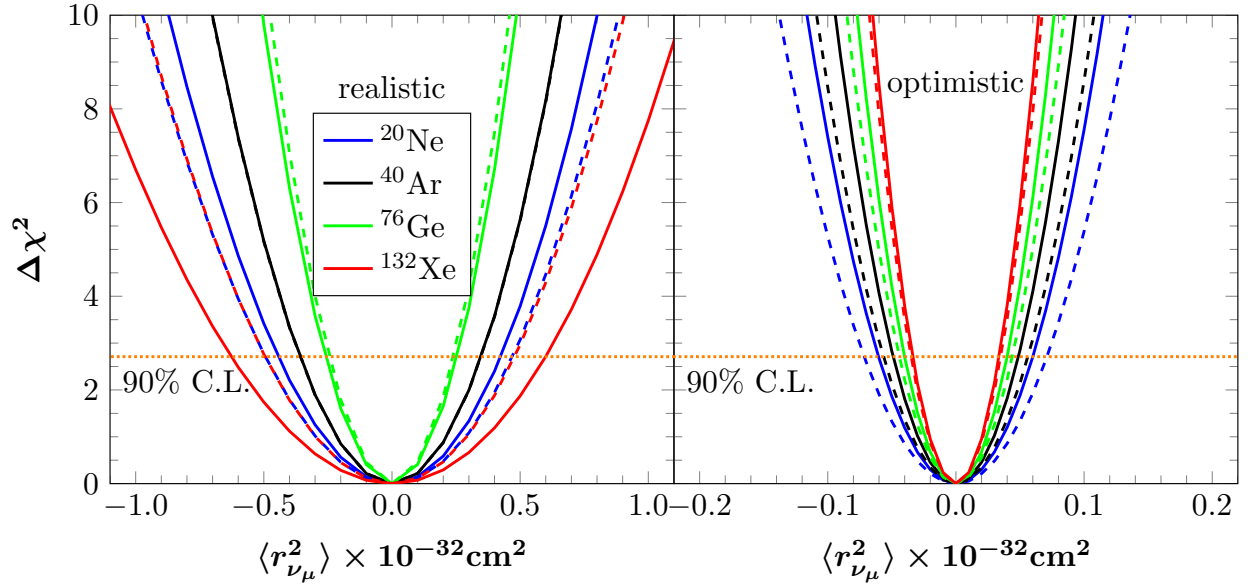


FIG. 8:  $\Delta\chi^2$  profile for the neutrino charge radius,  $\langle r_{\nu_\mu}^2 \rangle$  in units of  $10^{-32}\text{cm}^2$ , from the combined measurement of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ). Same conventions as in Fig. 1 are used.

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